Dear Dr.

Thank you very much for your constructive evaluation of our paper. Please, accept our apologies for not returning the revision in time – this is due to a prolonged field trip of two authors, where we had no electronic connections and from which returned on July the 1st only. The extension of the revision time that you allowed for is greatly appreciated.

We are now sending you our revised manuscript where we have attended to the comments of Referee 2. (Referee 1 did not ask for a revision; we appreciate his/her evaluation of the potential importance of our work.) Below is a detailed response to the issues raised by Referee 2. It is followed by a description of changes made accordingly to the text.

The following major changes have been implemented:

(1) we clarified the meaning of a physical driver of circulation in the context of the issues discussed in our paper;

(2) we incorporated the comments and references given by the referee regarding Hadley circulation research into discussion;

(3) prompted by the referee's interest in the precipitation issue, we showed how the condensation-induced pressure gradient can be estimated from the regional difference (evaporation minus precipitation). This estimate is in agreement with our original estimate made from consideration of vertical gradients of air and vapor pressure, thus providing further support for our conclusions.

We would like to note that in our work we are offering a draft of what from the basic physical principles appears as a plausible alternative to the classical view of what governs the atmospheric dynamics (differential heating). Indeed, the current understanding of the general circulation is recognized as incomplete. In his comprehensive review, Schneider (2006, p. 682) explicitly admitted the *lack of necessary theoretical concepts* to treat the dynamic and kinematics issues associated with water vapor. In such situation we believe that a wider scrutiny of our propositions by the research community may lead to advances in the field.

We hope that our revisions help sharpen our message and we are willing to undertake further efforts in this direction if such are judged necessary. My colleagues and I are looking forward to hearing from you in due course.

Yours very sincerely,

Anastassia Makarieva

1 Response to comments

We thank the referee for stimulating comments.

1. Referee 2 writes:
"This paper is interesting but somewhat confused. Without dwelling on the details of calculating the effect of precipitation on surface pressure, the attempt to relate such changes to large scale motion systems seems to ignore the fact that they are referring to balanced flows. Thus, pressure gradients per se do not drive the Hadley circulation. Rather, the momentum balance leads to circulations that maintain pressure gradients consistent with geostrophy."

We would like to clarify our logic on this essential issue. The fundamental point we focus at is - where does the momentum come from? In the absence of a physical circulation driver, the frictional dissipation in the realistic balanced Hadley flow would ultimately zero the kinetic energy of winds. On the other hand, according to Newton's law, any air parcel can only start moving if acted upon by a force. In the horizontal direction, there are two types of forces (apart from friction), the pressure gradient force and Coriolis force. Since the latter force is proportional to velocity, the Coriolis force cannot make a motionless air volume move. Instead, it only modifies an existing movement that is originally driven by a pressure gradient force.

On the other hand, in a balanced flow the velocity field and pressure field are uniquely related. E.g., in geostrophic balanace if one knows wind velocity and rotation frequency, one can calculate the pressure gradient. Conversely, if one knows the pressure gradient, one can retrieve the velocity of the balanced flow. Indeed, if one generates and sustains a horizontal pressure gradient in a gas medium, there will be an air flow, as prescribed by Newton's law and Navier-Stokes equations. For example, Murphree and van den Dool (1988) (we cited this work in our text) used the observed pressure gradients to feed them into the hydrodynamics equations and retrieve the observable wind velocities in the tropics.

In this sense we agree with the referee that once a pressure gradient is generated, it is not relevant for the resulting air flow how it has been generated. We also agree that the flow itself can modify an original pressure gradient. Moreover, we indicate in the text that the condensation effect on pressure is non-linear and involves a positive feedback between the flow and the condensation process (Section 3).

In climate theory the non-uniformity of solar energy distribution over the Earth's surface has been conventionally considered as the primary driver of circulation. Our message is that the presence of the condensable component in the Earth's atmosphere represents a different and important physical mechanism that can drive motion by generating horizontal pressure gradients on an isothermal surface in the absence of (external) differential heating.

2. Referee 2 writes:
"The actual way the pressure gradients are produced is essentially irrelevant though it would be potentially interesting if the mechanism involved precipitation."

In the revised version we show how the condensation-induced pressure gradient can be estimated from the regional precipitation minus evaporation difference. This estimate is in agreement with our original estimate (Eq. 13) made from consideration of the vertical gradients of air and vapor pressure, thus providing further support for our conclusions.

3. Referee 2 writes:
"The fact that Held and Hou do not provide a quantitatively realistic description of the Hadley circulation is almost certainly due to the omission of eddies (Robinson, 2006, JAS, Walker and Schneider, 2004, GRL, 2006, JAS) and the assumption of equinoxial conditions (Lindzen and Hou, 1988, JAS)."

This comment relates to the last paragraph of our paper. Here our intended message has been that despite much important work exemplified by the papers cited by the referee, the theory of general circulation remains incomplete. In a recent review, Schneider (2006) characterized the theory as still being "within reach"- and this for a dry atmosphere only. Water vapor issues have been identified as an explicit challenge. In our revised text we incorporate the papers mentioned by the referee to strengthen our point of the continued discussions around the general circulation theory.

2 Changes to the text

1. The following paragraph has been added to the end of Section 3 "The physical meaning of condensation-induced pressure gradients":

One reviewer has challenged us to better consider the mechanisms governing atmospheric circulation as these modify atmospheric pressure gradients in the balanced flow. Indeed, in a stationary balanced flow like that of Hadley circulation the pressure gradient force acting on the air is balanced by other forces, including those associated with turbulent friction and rotation. In the simplest case of geostrophic balance the pressure gradient force is balanced by the velocity-dependent Coriolis force. This means that if one knows the pressure gradient force, one can calculate wind velocity, and vice versa. For example, *Murphree and Van den Dool* (1988) used the observed tropical pressure gradients in the equations of hydrodynamics to derive the observable wind speeds. Importantly, the magnitude of the turbulent friction force and Coriolis force depend on air velocity and disappear if the velocity is zero. Thus, these forces do not act on motionless air and cannot make it move. In contrast, the pressure gradient force acting on air makes it move and accumulate (or sustain) the kinetic energy that otherwise continuously dissipates. This initial motion leads to the appearance of the velocity-dependent forces which, in turn, can modify the pressure field and the resulting pattern of the balanced flow. It is in this sense that a physical process that generates pressure gradients is the primary driver of circulation. In the absence of such a process the momentum balance of the stationary flow would be destroyed by frictional dissipation. As is clear from our estimates (13,14), the condensation-induced pressure gradients are of sufficient magnitude for the dynamic effects of condensation to play a major role in sustaining the observed Hadley circulation.

2. Prompted by the referee's interest in the precipitation issue, we showed how the condensation-induced pressure gradient can be estimated from the regional difference (precipitation minus evaporation), see Eq. (14) in the revised text.

3. The Discussion has been revised. We incorporated the comment and references cited by Referee 2. We also added reference to a recent paper by Chikoore and Jury (2010) which appears to be the first empirical study documenting an airflow associated with phase transitions of water vapor.

Here we wish to draw the attention of climate theorists to what we consider a major and undeservingly neglected physical mechanism that, as we propose, may influence and perhaps govern many aspects of atmospheric dynamics. In our approach we focus on the driving force behind, rather than the pattern of, atmospheric motion. Our proposal is that the atmosphere moves because of condensation – under our theory it is condensation which produces pressure gradients that are translated into winds. We start by noting that if there was no driving force the atmosphere would be static. We seek to clarify the driving forces behind the existing circulation. If the pressure gradients we identify occur in nature they will by necessity produce atmospheric movement. Indeed, according to Newton's law as embedded into the equations of hydrodynamics, the motion occurs only because a pressure gradient force has acted on the atmospheric air.

We note that currently in the atmospheric science there is both a place and a need for new approaches. Modern global circulation models do not satisfactorily account for the water cycle of the Amazon river basin, with the estimated moisture convergence being half the actual amounts estimated from the observed runoff values (*Marengo*, 2004). Major problems have been identified with the prevailing thermodynamic approach to describing hurricanes (*Smith et al.*, 2008; *Makarieva et al.*, 2010). Furthermore, so far it has not been possible to derive a quantitatively realistic theory of Hadley circulation based on the effects of differential heating alone (*Held and Hou*, 1980; *Fang and Tung*, 1999; *Schneider*, 2006). With efforts to address this challenge ongoing (e.g., *Lindzen and Hou*, 1988; *Robinson*, 2006; *Walker and Schneider*, 2005, 2006), in a recent review *Schneider* (2006) admitted that for a dry atmosphere such a theory just hopefully remains *within reach*. The problems of addressing the role of atmospheric moisture and, particularly, *lack of relevant theoretical concepts*, were identified as a persistent challenge. Meanwhile the incomplete understanding of the general circulation in the research literature precludes a theory-based analysis, from fundamental physical principles, of the role of latitudinal atmospheric mixing in stabilizing the Earth's thermal regime important: a key issue in debates concerning climate sensitivity (e.g., *Lindzen and Choi*, 2009; *Trenberth et al.*, 2010). Remarkably, all these challenges concern atmospheric movements with a conspicuous potential to be influenced by water vapor. We believe that condensation-induced dynamics will yield meaningful insights into these and many other important issues.

The basic physical mechanisms underlying the driving force behing atmospheric motion and their potential magnitudes are of fundamental significance. Atmospheric theorists have tended to ascribe atmospheric movement to temperature gradients and buoyancy-driven convection - while such mechanisms appear widely accepted, many essential issues, as illustrated briefly above, remain unresolved. Here we offer a new and credible alternative mechanism for a rigorous scrutiny by the research community. It will be fascinating to see how the outlined physical mechanism can be incorporated in integrated picture of atmospheric motion. We foresee some years of fruitful advances based on studying the air motion associated with the phase transitions of water both theoretically and empirically (see, e.g., *Chikoore and Jury*, 2010).

4. We have reviewed all the text to increase clarity and reduce the chances of misunderstanding.